(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 February 2003 (20.02.2003)

PCT

(10) International Publication Number
WO 03/014773 A2

(51) International Patent Classification[7]: G02B

(21) International Application Number: PCT/US02/25054

(22) International Filing Date: 7 August 2002 (07.08.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/310,477 7 August 2001 (07.08.2001) US

(71) Applicant: CORNING INCORPORATED [US/US]; 1 Riverfront Plaza, Corning, NY 14831 (US).

(72) Inventors: GRAY, Stuart; 370 E. Second Street, Corning, NY 14830 (US). WILDEMAN, George, Francis; 54 Overbrook Road, Painted Post, NY 14870 (US).

(74) Agent: SHORT, Svetlana, Z.; Corning Incorporated, 1 Riverfront Plaza, Patent Department, SP-TI-3-1, Corning, NY 14831 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW.

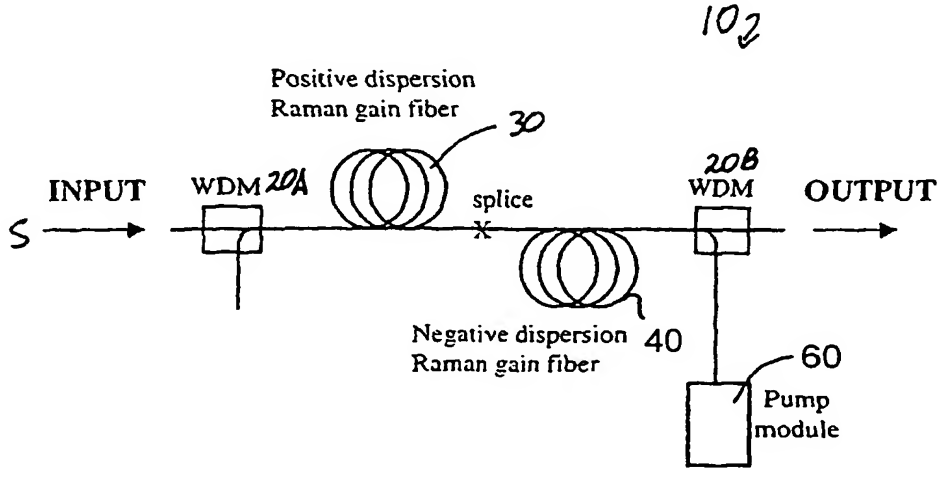
(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

FP04-0024-00WO-SE
04.7.-5
SEARCH REPORT

(54) Title: DISPERSION MANAGED DISCRETE RAMAN AMPLIFIERS



(57) Abstract: An optical amplifier comprises: (i) an input port for providing optical signal to the amplifier; (ii) an output port for providing amplified optical signal out of the amplifier; (iii) at least two optical fibers, one optical fiber having positive dispersion D1 of greater than 10 ps/nm/km in a 1550 nm to 1620 nm wavelength range, the other fiber having negative dispersion D2 of less than -5 ps/nm/km in a 1550 nm to 1620 nm wavelength range, wherein the length of each of said optical fiber is chosen to provide the amplifier with a predetermined amount of dispersion.

WO 03/014773 A2

DISPERSION MANAGED DISCRETE RAMAN AMPLIFIERS.

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application, Serial Number 60/310,477, filed 8/7/01 entitled Dispersion Managed Discrete Raman Amplifiers, by Stuart Gray and George F. Wildeman.

FIELD OF THE INVENTION

[0002] This invention generally concerns Raman optical amplifiers, and is particularly directed dispersion managed discrete Raman amplifiers.

BACKGROUND

[0003] Optical amplifiers for amplifying photonic signals transmitted through optical fiber networks are well known in the art. Such amplifiers are used to extend transmission distances and to compensate for losses from various network elements. Presently, there are several known types of optical amplifiers, including erbium-doped fiber amplifiers (EDFAs), and Raman amplifiers.

[0004] EDFAs typically comprise at least one pump laser whose output is optically coupled to at least one coil of erbium-doped optical fiber. In operation, the output of the pump laser excites the atoms of the erbium-dopant within the fiber. These excited atoms release their excess energy in proportion to the strength of the incoming optical signal, which results in an amplified output. By contrast, Raman amplifiers achieve amplification without the need for erbium-doped optical fibers. Therefore, Raman amplifiers may use optical fibers without Er dopant as their gain fiber.

[0005] In one type of Raman amplifier, the output of a pair of orthogonally polarized pump-diode lasers provides backward propagating pump power in the gain fiber. Alternatively, a single pump and a de-polarizer may also be utilized to provide pump power in the gain fiber. Forward-propagating signals are amplified in the gain fiber by higher energy (shorter wavelength) pump photons scattering off the vibrational modes of the optical

fiber's lattice matrix and coherently adding to the lower-energy (longer wavelength) signal photons.

[0006] Raman amplifiers may be one of two types, depending upon the type of the gain fiber used therein. Distributed Raman amplifiers advantageously use the silica based optical transmission fiber itself as the gain fiber. By contrast, discrete Raman amplifiers typically utilize their own silica based optical fiber as the gain fiber. While the dopant used in the gain fiber of a discrete Raman amplifier is typically the same as used in the optical transmission fiber (e.g., germanium), the gain fiber of the discrete Raman amplifier usually contains higher concentrations of dopant (such as germanium) than a conventional optical transmission fiber and is designed to operate with a decreased fiber effective area.

[0007] The Raman gain efficiency of an optical fiber as a Raman amplifier is characterized by a figure of merit defined as

$$F = \frac{G_R}{A\alpha_p}$$

where G_R is the Raman scattering coefficient of the optical fiber material at the specified pump wavelength, A is the effective area of the optical fiber and α_p is the attenuation of the optical fiber at the pump wavelength.

[0008] Silica based Ge-doped optical fiber manufactured for use in discrete Raman amplifiers has a small effective area A, typically about 10-20 μm^2. The addition of germanium to the silica based optical fiber increases the Raman scattering coefficient, G_R. Because of this, the figure of merit F of this optical fiber is typically greater than 20 for pump wavelengths in the 14xx nm band. In comparison the figure of merit for a typical optical transmission fiber is about 7 or 8.

[0009] High levels of germanium dopant and small effective areas of the fibers utilized in discrete Raman amplifiers have an undesirable side-effect in that the nonlinear refractive index n_2/A of these fibers is very high compared to that of transmission fibers. The net refractive index is defined by the equation $n=n_0 + n_2P/A$, where n_0 is the linear part of the net refractive index (which is independent of the optical power P propagating through the fiber) and n_2/A is the nonlinear part (which is dependent on the optical power P propagating through the fiber). For example, n_2/A in a Discrete Raman gain fiber is about $3x10^{-9}$ W^{-1},

compared to about $0.3x10^{-9}$ W^{-1} in a transmission fiber, such as for example, SMF-28™ available from Corning, Inc. of Corning, NY. The large nonlinear refractive index can lead to unwanted nonlinear interactions such as self-phase modulation (SPM), cross-phase-modulation (XPM) and four-wave mixing (FWM). In addition, this type of highly doped and small effective area fiber typically has dispersion in the range –20 to –30 ps/nm/km. Typical optical transmission fibers have dispersion values of +5 to +19 ps/nm/km.

[0010] System penalties from FWM can be significantly reduced or eliminated by using gain fibers which have a high dispersion (greater than |20| ps/mn/km) to prevent phase-matching between different signal channels. However, the gain fiber utilized in discrete Raman amplifiers is generally several kilometers in length and using gain fibers which are highly dispersive fibers will result in the discrete Raman amplifier with a significant net negative dispersion.

[0011] A highly dispersive discrete Raman amplifier will be a disadvantage in systems employing dispersion managed cable or dispersion managed fiber where either no dispersion or only a limited amount of dispersion is required at site of the amplifier.

SUMMARY OF THE INVENTION

[0012] According to present invention an optical amplifier comprises: (i) an input port for providing optical signal to the amplifier; (ii) an output port for providing amplified optical signal out of the amplifier; (iii) at least two optical fibers, one optical fiber having positive dispersion D_1 of greater than 10 ps/nm/km in a 1550 nm to 1620 nm wavelength range, the other fiber having negative dispersion D_2 of less than –5 ps/nm/km in a 1550 nm to 1620 nm wavelength range, wherein the length of each of said optical fiber is chosen to provide the amplifier with a predetermined amount of dispersion.

[0013] According to one embodiment of the present invention a discrete Raman amplifier comprises: (i) an input port providing optical signal to said amplifier; (ii) an output port providing amplified optical signal out of the amplifier; (iii) at least two optical fibers, one optical fiber having positive dispersion D_1 of greater than 10 ps/nm/km in a 1550 nm to 1620 nm wavelength range, and length of 5 m to 2.5 km, the other fiber having a negative dispersion D_2 of less than –5 ps/nm/km in a 1550 nm to 1620 nm wavelength range and length of 5 m to 2.5 km, wherein the length of each of the two optical fibers is chosen to

provide this amplifier with substantially zero dispersion over the signal range, such that the dispersion of the amplifier is less than 25 ps/nm over the signal wavelength range.

BRIEF DESCRIPTION OF THE DRAWING

[0014] The invention will be described through the embodiments and the attached drawing in which:

[0015] Figure 1 is a schematic illustration of the first embodiment of a dispersion managed discrete Raman amplifier;

[0016] Figure 2 is a schematic illustration of the second embodiment of a dispersion managed discrete Raman amplifier.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0017] According to an embodiment of the present invention a discrete Raman amplifier utilizes at least two optical fibers with opposite signs of dispersion whose relative lengths are adjusted to give either a net zero dispersion, or a desired amount of dispersion. A net zero dispersion is the dispersion of less than 25 ps/nm over the signal wavelength range. Additionally, the dispersion slopes of the optical fibers could be designed to have opposite signs to achieve dispersion slope compensation. Dispersion slope is defined as the rate of change of dispersion with wavelength. Dispersion slope compensation compensates for the dispersion of an optical amplifier over a broader signal wavelength range ($1550\ nm < \lambda < 1620\ nm$, for example) than that achieved by an amplifier that utilizes non-slope compensating fiber.

[0018] A discrete Raman amplifier may utilize at least two sections of optical fiber (one with positive dispersion and one with negative dispersion) in a single stage, where these fiber sections are spliced together. Such an amplifier may be either a single amplification stage or a multi amplification stage device. Alternatively, in a multi stage amplifier a different fiber may be used in each amplification stage. For example, the first amplification stage may have gain fiber with positive dispersion, while another stage may have gain fiber with negative dispersion. Alternatively, the first amplification stage may have gain fiber with negative dispersion, while another stage may have gain fiber with positive dispersion. Two

embodiments of the dispersion compensated discrete Raman amplifiers are shown schematically in Figures 1 and 2 and are described in detail later in the specification. Three or more fibers with different dispersion slopes may be needed to achieve the desired dispersion slope compensation.

[0019] As mentioned above, the typical gain fiber utilized in discrete Raman amplifiers has a large negative dispersion. In order to achieve a net dispersion of zero in the discrete Raman amplifier it is desirable that this amplifier include optical fiber with large negative dispersion (D<-5 ps/nm/km, and preferably D<-10 ps/nm/km) and optical fiber wit large positive dispersion. However, optical transmission fibers with a large (>20 ps/nm/km) positive dispersion D have a very large effective area. Because the effective area of the optical fiber is inversely proportional to figure of merit F, optical fibers with large effective areas have low figures of merit, and therefore, low Raman gain efficiency. Examples of such fibers are optical transmission fibers SMF-28™ fiber (D=+17 ps/nm/km and A = 80 μm^2) and Vascade™ (D=+19 ps/nm/km and A = 100 μm^2), both available from Corning, Incorporated, of Corning, NY. In order to overcome the problem of the low Raman gain efficiency it is preferable that the positive dispersion fiber be an optical photonic crystal fiber (PCF), or another positive dispersion fiber with small effective area (A<40 μm^2). Photonic crystal fiber is disclosed, for example, in the article entitled, "All- silica single-mode optical fiber with photonic crystal cladding", by J.C. Knight et al., published in Optics Letters, vol. 21 pp 1547-1549 (1996) and is available, for example, from Crystal Fibre of Denmark. Photonic crystal fibers are manufactured with air holes in the fiber cladding and typically have very small effective areas (<15 μm^2). By adjusting the size and spacing of the air holes it is possible to make a PCF with a large positive dispersion at 1550 nm. For example, PCFs may have dispersion values as high as +50 ps/nm/km. These PCF fibers are described, for example, in the article entitled "Toward practical holey fiber technology: fabrication, splicing, modeling and characterization", by Bennet et al, published in Optics Letters vol. 24 pp 1203-1205 (1999). The small effective area of these PCFs will also increase their Raman gain efficiency compared to large effective area fibers.

[0020] Thus, according to one aspect of the present invention a discrete Raman amplifier utilizes at least two fibers with opposite signs of dispersion, where in the length of each fiber is chosen to provide a predetermined amount of dispersion (such as zero, for example). It is preferable that these fibers have opposite signs of dispersion slope to achieve the desired

dispersion slope compensation. For example, two fibers having opposite signs of dispersion and opposite signs of dispersion slope can achieve a net zero dispersion over a broad wavelength rage ($1550<\lambda<1620$, for example). Two fibers having opposite signs of dispersion but the same sign of dispersion slope can only achieve a net zero dispersion at one wavelength.

[0021] For example, fibers of positive and negative dispersion may be located in the same amplifier stage. Alternatively, fibers with positive and negative dispersion may be located in different amplifier stages. As stated above, the positive dispersion fiber may be a photonic crystal fiber. More specifically, **Figure 1** illustrates a discrete Raman amplifier **10** that includes a length of positive dispersion, positive slope fiber **30** coupled to a length of negative dispersion, negative slope fiber **40**. Fibers **30** and **40** are located in the same stage (the only stage) of this amplifier. An optical pump **60** is coupled to the fiber **40** via wavelength division multiplexer (WDM) **20B**. The pump light from the pump **60** propagates through fiber **40** and then through the fiber **30**, generating gain in counter propagating signal S. An optional second WDM **20A** located upstream of fiber **30** diverts unabsorbed pump light out of the Raman amplifier and prevents it from propagating through the rest of the transmission system. It is contemplated that the length for the fibers **30** and **40** would be between 50 meters to 5 kilometers. A typical length for each of these fibers would be 500 meters to 2 kilometers. The positive dispersion fiber **30** would preferably have a dispersion value D of over +10 ps/nm/km and most preferably more than +20 ps/nm/km. The negative dispersion fiber **40** would have a dispersion value D of less than –5 ps/nm/km, preferably less than –10 ps/nm/km and most preferably less than –20 ps/nm/km. In this embodiment the length of optical fibers **30** and **40** is 2 km. The dispersion of optical fiber **30** is 20 ps/nm/km at 1550nm. The slope S of this fiber is – 0.05 ps/nm^2/km. The dispersion of optical fiber **40** is -20 ps/nm/km at 1550nm. The slope S of the fiber **40** is 0.05 ps/nm^2/km.

[0022] **Figure 2** illustrates a discrete Raman amplifier **100** that includes two amplification stages. The first amplification stage includes a length of positive dispersion, positive slope fiber **130** coupled an optical pump **160** via a WDM **150A**. Another WDM, **120** is situated at at the input port of the amplifier **100**. This WDM **120** is located upstream of fiber **130** and diverts unabsorbed pump light out of the Raman amplifier **100** and prevents it from propagating through the rest of the transmission system. The second amplification stage is separated from the first amplification stage by an isolator **170**. This isolator **170** prevents

reflected signal from propagating into the first stage of the Raman amplifier **100** and also prevents ASE noise from the second stage into the first stage. Such ASE noise depletes the pump light and reduces the signal gain. The second amplification stage includes a length of negative dispersion, negative slope fiber **180**. An optical pump **200** is coupled to the fiber **180** via wavelength division multiplexer (WDM) **150B**. It is noted that the fibers **130, 180** have dispersion D, wherein D>|10|ps/nm/km. It is preferable that the absolute value of dispersions be in the range of 10 to 100 ps/nm/km, and more preferably that the absolute values of dispersions be 15 to 30 ps/nm/km. More specifically, in this embodiment, the dispersion of optical fiber **130** is 20 ps/nm/km at 1550nm. The slope S of this fiber is – 0.05 $ps/nm^2/km$. The dispersion of optical fiber **180** is -20 ps/nm/km at 1550nm. The slope S of the fiber **180** is 0.05 $ps/nm^2/km$. The invention can be applied to any type of Raman amplifier. The amplifier site may utilize multiple channel amplifiers and/or single channel amplifiers. The transmitted signal can be of any type and can be for any application.

[0023] The invention has been described through preferred embodiments. However, various modifications can be made without departing from the scope of the invention as defined by the appended claims and legal equivalents.

What is Claimed:

1. An optical amplifier comprising: (i) an input port for providing optical signal to said amplifier; (ii) an output port for providing amplified optical signal out of said amplifier; (iii) at least two optical fibers, one with a positive dispersion D_1 of greater than 10 ps/nm/km in a 1550 nm to 1620 nm wavelength range, one with a negative dispersion D_2 of less than –5 ps/nm/km in a 1550 nm to 1620 nm wavelength range, wherein the length of each of said optical fiber is chosen to provide said amplifier with a predetermined amount of dispersion.

2. The amplifier of claim 1, wherein fiber with the positive dispersion is a photonic crystal fiber.

3. The discrete Raman amplifier according to claim 1, wherein said predetermined amount of dispersion is substantially zero, such that the dispersion of the amplifier is less than 25 ps/nm over the signal wavelength range.

4. The discrete Raman amplifier according to claim 1, wherein $D_1 > 20$ ps/nm/km.

5. The discrete Raman amplifier according to claim 1, wherein $D_2 < -10$ ps/nm/km.

6. The discrete Raman amplifier according to claim 5, wherein $D_2 < -20$ ps/nm/km.

7. A discrete Raman amplifier comprising: (i) an input port providing optical signal to said amplifier; (ii) an output port providing amplified optical signal out of said amplifier; (iii) at least two optical fibers, one optical fiber having positive dispersion D_1 of greater than 10 ps/nm/km in a 1550 nm to 1620 nm wavelength range, and length of 5 m to 2.5 km, the other fiber having a negative dispersion D_2 of less than –5 ps/nm/km in a 1550 nm to 1620 nm wavelength range and length of 5 m to 2.5 km,, wherein the length of each of said optical fiber is chosen to provide said amplifier with a predetermined amount of dispersion.

8. The amplifier of claim 1 or 7 wherein said at least two optical fibers have opposite signs of dispersion slope.

9. The amplifier of claim 1 or 7, wherein both of said optical fibers are situated in one amplifier stage.

10. The amplifier of claim 1 or 7, wherein said at least two optical fibers are situated in different amplifier stages.

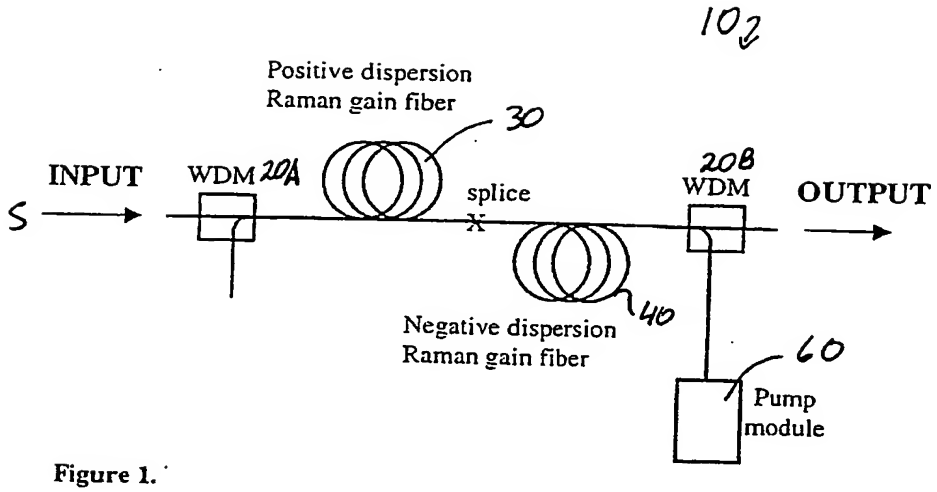


Figure 1.

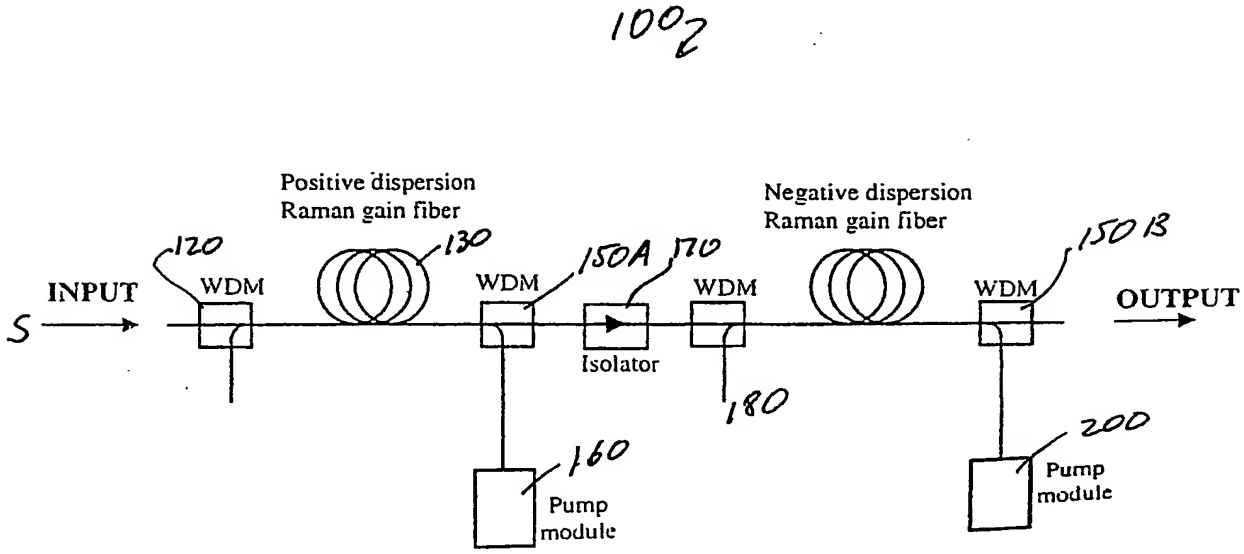


Figure 2.

THIS PAGE BLANK (USPTO)

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 February 2003 (20.02.2003)

PCT

(10) International Publication Number
WO 03/014773 A3

(51) International Patent Classification[7]: G02F 1/35, H01S 3/10

(21) International Application Number: PCT/US02/25054

(22) International Filing Date: 7 August 2002 (07.08.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/310,477 7 August 2001 (07.08.2001) US

(71) Applicant: CORNING INCORPORATED [US/US]; 1 Riverfront Plaza, Corning, NY 14831 (US).

(72) Inventors: GRAY, Stuart; 370 E. Second Street, Corning, NY 14830 (US). WILDEMAN, George, Francis; 54 Overbrook Road, Painted Post, NY 14870 (US).

(74) Agent: SHORT, Svetlana, Z.; Corning Incorporated, 1 Riverfront Plaza, Patent Department, SP-TI-3-1, Corning, NY 14831 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW.

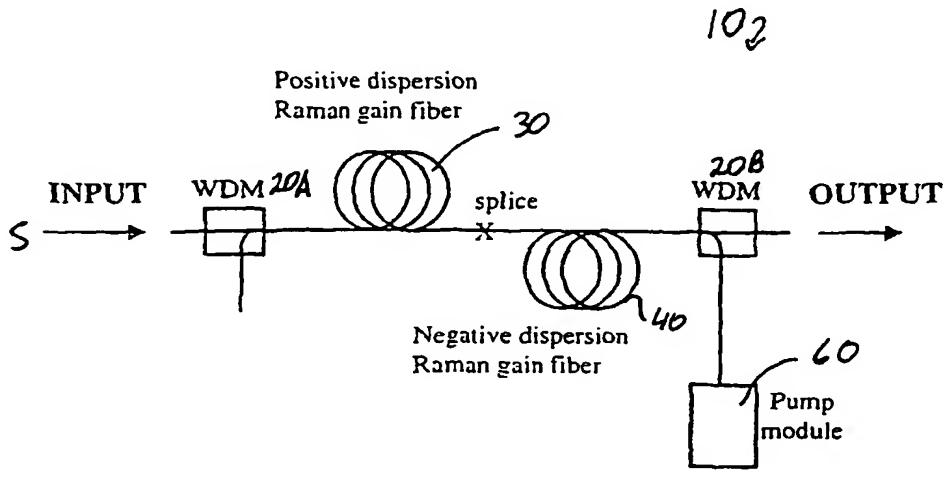
(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(88) Date of publication of the international search report:
30 October 2003

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: DISPERSION MANAGED DISCRETE RAMAN AMPLIFIERS



(57) Abstract: An optical amplifier (10) comprises: (i) an input port (20a) for providing optical signal (S) to the amplifier; (ii) an output port (20b) for providing amplified optical signal out of the amplifier; (iii) at least two optical fibers, one optical fiber having positive dispersion D1 of greater than 10 ps/nm/km in a 1550 -1620 nm wavelength range, wherein the length of each of said optical fiber is chosen to provide the amplifier with a predetermined amount of dispersion.

WO 03/014773 A3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US02/25054

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02F 1/35; H01S 3/10
US CL : 359/334, 337, 337.4, 337.5; 372/3, 6

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 359/334, 337, 337.4, 337.5; 372/3, 6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
JAPIO, DWPX, INSPEC, USPAT, US-PGPUB, EPO, JPO, DERWENT

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,887,093 A (HANSEN et al) 23 March 1999, columns 1-3, 5, 7 and 8.	1 and 3-6
---		---
Y		2 and 7-10

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
07 August 2003 (07.08.2003)

Date of mailing of the international search report
20 AUG 2003

Name and mailing address of the ISA/US
Mail Stop PCT, Attn: ISA/US
Commissioner for Patents
P.O. Box 1450
Alexandria, Virginia 22313-1450
Facsimile No. (703)305-3230

Authorized officer
Nelson Moskowitz
Telephone No. (703)306-4177

Form PCT/ISA/210 (second sheet) (July 1998)

BNSDOCID: <WO_____03014773A3_I_>